

INTERMITTENCY AND COHERENT STRUCTURES NEAR THE AIR-SEA INTERFACE IN THE PLANETARY BOUNDARY LAYERS

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LONG-TERM GOAL

Our primary, long-term objective is to understand turbulence in the planetary boundary layers (PBLs) on the basis of its calculation through large-eddy simulation (LES) techniques. There are many aspects to achieving this understanding: exploring the variety of large and meso-scale environments that occur in nature; achieving sufficiently large Reynolds number (Re) so that the intermittent inertial behavior is qualitatively similar to that in nature; determining the space-time distributions of and controlling circumstances for the cascade, dissipation, and air-sea fluxes; determining the character and dynamical roles of coherent structures in the PBL; examining the interactions of surface gravity waves and PBL turbulence; discovering the degree to which significant coupling occurs between the oceanic and atmospheric PBLs; and developing better PBL and air-sea flux parameterizations.

SCIENTIFIC OBJECTIVES

The recent FLIP experiments show intriguing departures from traditional Monin-Obukhov scaling in the surface layer when surface waves are present. This is especially apparent in the measurements of energy dissipation (Jim Edson, WHO). An interpretation of these results is that waves can be an additional source or sink of energy depending on their phase speed relative to the wind at 10 meters. Our scientific objective is to use our 3-D LES numerical model to study the effects of surface gravity waves on the turbulence in the atmospheric PBL, and in particular to see if waves alter Monin-Obukhov scaling in our numerical simulations. In addition, we wish to examine the effect of surface gravity waves on Langmuir circulations in the oceanic PBL.

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APPROACH

We are using computational techniques of nested grids to achieve higher resolution in the surface layer: an outer grid deals with the PBL as a whole, and (an) inner grid(s) have finer and more nearly isotropic spatial grid spacing in the surface layer. This allows us to simulate eddies as small as just a few meters within the atmospheric surface layer (and about a factor of ten smaller within the oceanic surface layer). To obtain numerical solutions for turbulent flow over (or beneath) surface gravity waves we have been modifying our LES to allow moving surface fitted grids

WORK COMPLETED

In the contract period to date, we have:

1. Calculated and analyzed LES solutions using the initial version of the model for a range of stratification profiles and surface buoyancy flux and stress conditions (Moeng and Sullivan, JAS, 1994);
2. Developed a new sub-grid-scale parameterization that yields Monin-Obukhov similarity profiles nearly independent of grid resolution (Sullivan, McWilliams, Moeng, BLM, 1994);
3. Completed development of a nested-grid technique that permits high resolution near the air-sea surface (Sullivan, McWilliams, Moeng, BLM, 1996);
4. Completed a detailed analysis of coherent structures in a neutrally stratified PBL using flow visualization and conditional sampling techniques (Lin, McWilliams, Moeng, Sullivan, Physics Fluids, 1996);
5. Analyzed solutions for LES with Stokes drift effects from surface gravity waves as represented in the Craik-Leibovich theory (McWilliams, Sullivan, Moeng, JFM, 1997);
6. Examined the effect of variable surface roughness in a neutral PBL (Lin, Moeng, McWilliams, Sullivan, Physics Fluids, accepted); and
7. Initiated an effort to understand the interaction between surface gravity waves and atmospheric PBLs in the surface layer (Sullivan, McWilliams, Moeng, 12th Symposium on Boundary Layers and Turbulence, 1997).

The results of our scientific research noted in items 1 through 7 above have been presented at scientific and ONR PI meetings, reviewed by peers, and archived in scientific journals. This expanding body of LES solutions (at higher resolution, with Stokes drift effects, in different synoptic regimes, etc.) has been used to explore the detailed relationships between momentum and buoyancy fluxes and coherent structures in shear, convective, and wave-influenced PBLs. These studies suggest a strong link between coherent structures and intermittent, intense flux events.

RESULTS

In our first attempt at modeling the effect of surface gravity waves in LES, we adopted our "flat" nested LES model and accounted for the surface gravity waves solely through modifications to the surface boundary conditions. We used linear wave theory for the forms of the surface velocities and wave height along with the assumption of small wave slope. A novel surface drag

law that accounts for a portion of the resolved stress due to the pressure drag was also implemented. These boundary conditions were used in a nested grid LES that covers a larger numerical domain of (840,840,700)m with a grid resolution of (11.6, 11.6, 7)m, and a nested numerical domain of (840, 840, 35)m with a grid resolution of (3.9,3.9,1)m. The conditions of the flow are weak winds and nearly zero surface heat flux. Properties of the surface gravity wave are chosen compatible with the dominant wave observed during the recent FLIP experiments. Several simulations were performed with the ratio of the wind speed at 10 meters (U_{10}) to the wave phase speed (c) as the control parameter, i.e., U_{10}/c .

Results from this first air-wave interaction model are shown in Figures 1 and 2. Average mean velocity profiles are shown in Figure 1, while the vertical velocity variance and root-mean-square pressure are plotted in Figure 2, for four different values of U_{10}/c . Our interpretation of these results is that when the wind speed at 10 meters and the phase speed of the waves are comparable in magnitude a resonance like situation occurs and the wave induced motions interact strongly with the background turbulence. Notice that when $U_{10}/c = 1.06$ the mean velocity profile departs noticeably from Monin-Obukhov theory and the effect of the surface waves extends out to $z/z_i = 0.05$ or nearly one wavelength (approximately 35m) above the $z = 0$ surface. This type of surface wave model, i.e., accounting for waves through a modification to the lower boundary conditions, is expected to be only applicable to small wave slopes. We found that at waveslopes > 0.01 an unrealistically large value of fluctuating pressure was generated near the surface.

Encouraged by our results and experience with the "flat" nested LES code with modified surface wave boundary conditions, we have been revamping our LES code to accommodate surface fitted grids. This capability will allow us to resolve the turbulent flow about a moving monochromatic wave without making crucial assumptions about the surface boundary conditions. The new code is also directly applicable to the oceanic PBL where we will be able to examine the effect of surface waves on Langmuir circulations and PBL turbulence in the ocean. As a testbed we have generated a 2-D version of our 3-D LES code on a workstation and have been testing our surface fitted algorithm on Rayleigh-Bernard convection problems. We expect this new numerical technology to be implemented in our 3-D LES code within the next year.

IMPACT/APPLICATION

The nested grid LES code we have developed has direct applications to surface layer flows in both the atmospheric and oceanic PBLs as demonstrated above. In addition, we have used the same nested grid capability to examine entrainment processes in convectively and radiatively driven atmospheric PBLs. Two publishable manuscripts were produced and several scientific presentations were given on our entrainment results. We anticipate that with the completion of our surface fitted grid capability we will be able to explore an even wider range of PBL flows and obtain more definitive comparisons with experimental results.

RELATED PROJECTS

We have had several discussions with Carl Friehe (UC Irvine) concerning his recent wind-wave experiments from FLIP. In addition, we recently sponsored a visit by Jim Edson (Woods Hole Institute of Oceanography) to speak at NCAR on his atmospheric measurements also obtained during the FLIP cruise.

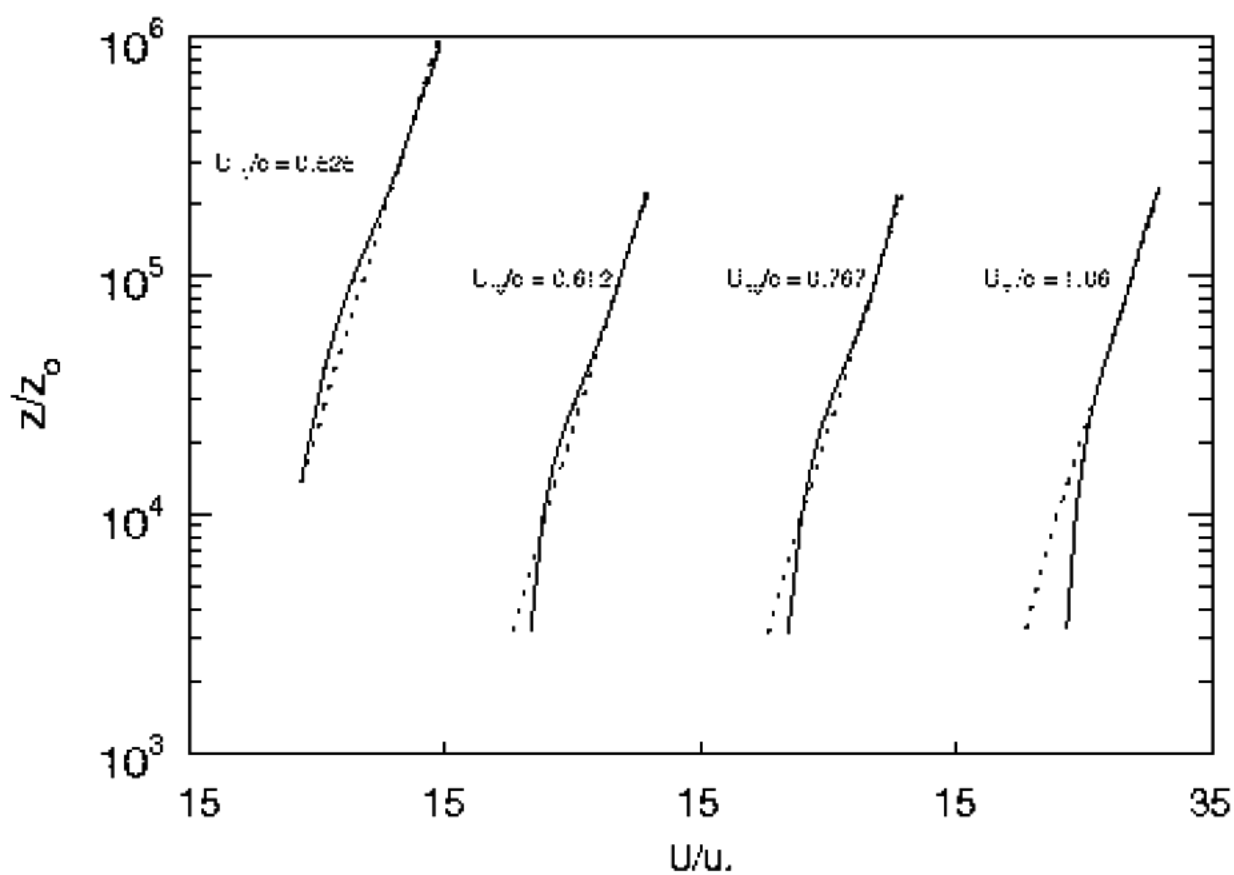


Figure 1: Normalized Mean Velocity Profiles for Different Wave Conditions

U is the average wind speed, u_* is the friction velocity, z_0 is the roughness height, and U_{10}/c is the ratio of the velocity at 10 meters to wave phase speed c .

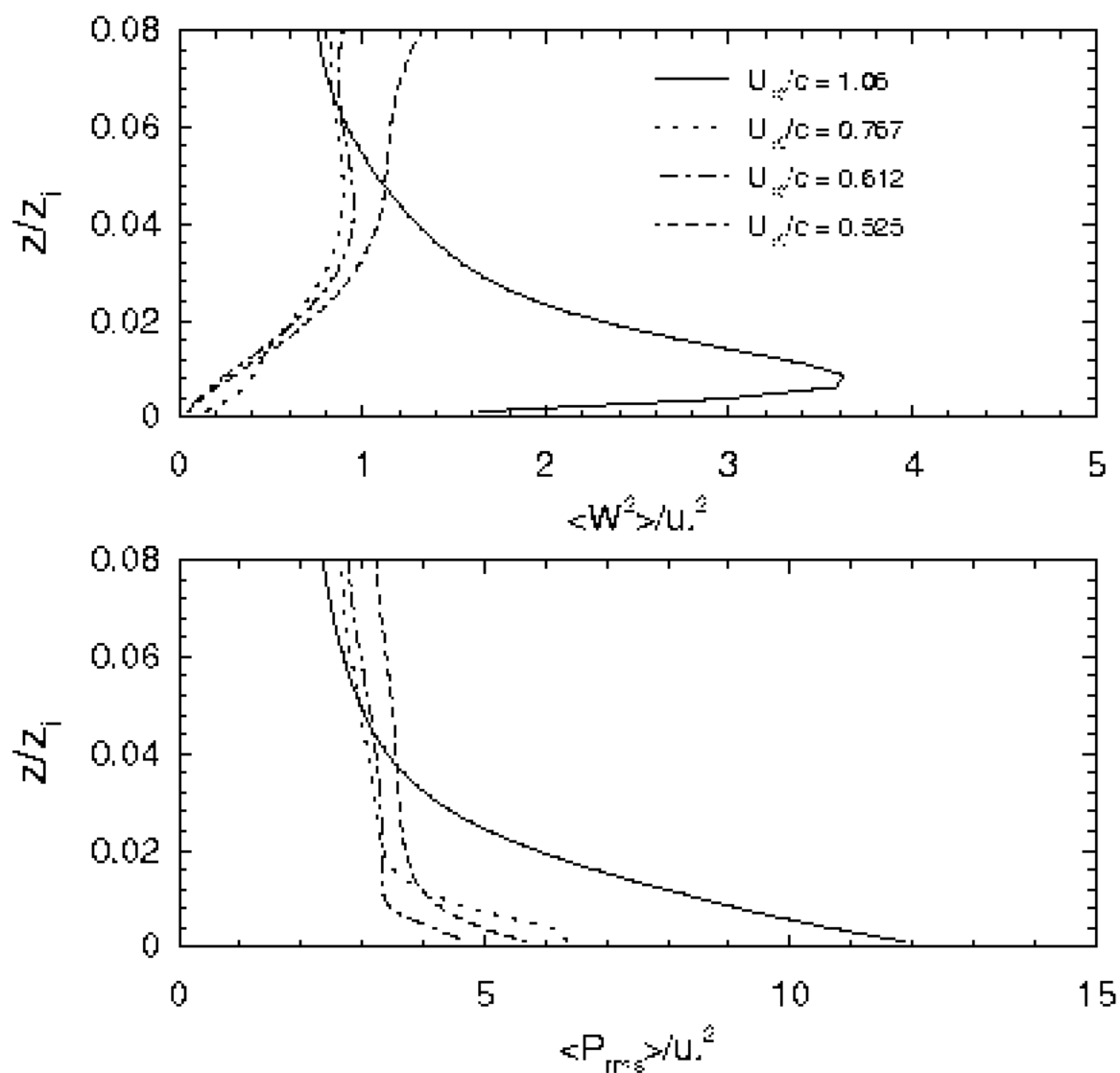


Figure 2: Profiles of Vertical Velocity Variance $\langle w^2 \rangle / u_*^2$ and *rms* Pressure $p' / \rho u_*^2$ for Different Wave Conditions, Boundary Layer Height $z_i = 500\text{m}$.